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INITIATION, STABILITY AND LIMITS OF DETONATION FOR ADVANCED STABLE/AIR-BREATHING AND HYBRID PROPULSION ENGINE DESIGN

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13. ABSTRACT

During this period research was carried out on the influence of initial conditions on limits of detonability in hydrocarbon-air mixtures, with emphasis on the influence of detonation tube shape. Experimental results for circular cross-section tubes indicated that the detonation limit is a linear function of reciprocal tube diameter. For square cross-section tubes experimental results obtained seem to indicate that the limits of detonability are slightly wider than for circular, and neither hydraulic radius, tube area, or narrowest tube dimension determines limits of detonability. However, measurements in rectangular tubes with various cross sections seem to indicate that for rectangular cross section tubes there exists a very close correlation between the limits of detonability and the narrowest hydraulic diameter of the tube, as long as one side is not too narrow. Investigation of development was also carried out including study of the stability of propagation of spherical flames in CH_4, H_2, C_2H_4, and C_2H_2 with increasing oxygen content in the air, using soap bubble techniques for determining flame speed. In all systems investigated no indication of flame acceleration or transition to detonation was observed. Results indicated that external mechanisms were responsible for flame acceleration and transition to detonation in experiments of other researchers. Some of the experimental results have been reported at the de Chema conference in Feb 1972.

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DETONATION

LIMITS OF DETONABILITY

INFLUENCE OF TUBE SHAPE ON STABILITY

SPHERICAL EXPLOSIONS

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INFLUENCE OF THE SHAPE OF THE DETONATION TUBE

ON THE LIMITS OF DETONABILITY

Introduction

Limits of detonability are normally determined in detonation
tubes of circular cross section. In these tubes one finds
that the limit concentration of the mixture is propor-
tional to the reciprocal tube diameter, except at tube dia-
meters, which are close to the limiting tube diameter, below
which no detonation exists, even in stoichiometric mixtures.
For reliable determinations of limits of detonability two
points are very important:

1. the test tube must be long enough. This means that
   the tubes must be so long, that further increase of
   the length of the tube does not influence the limit
   of detonability. (It may, however, reduce the un-
   certainty of the limit concentration, which should
   go to zero for infinite tube length.)

2. The detonation must be ignited by another detonation,
   so that it starts as an overdriven detonation and
   reaches its stability limit from "above". Other-
   wise one normally obtains limits which are narrower.

A simple minded explanation of the limits of detonability
is based on the observation that close to the limit nearly
always single headed spin appears, the frequency of which
is essentially determined by the tube diameter and the
sound velocity in the burned gases. It is driven by energy

addition to the vibration which due to Raleighs statement
takes place in the right phase of the vibration. If the
chemical reaction becomes to slow, to fit that condition
(details of the processes do not alter that result) than
the detonation fails. This explanation allows to describe
the experimental findings in circular tubes if one takes
into account, that the wall generated expansion waves
are stronger in narrow than in wide tubes, so that they
compensate for the slightly higher temperature in the
burned gas of limit detonations in tubes of small diameter
and the C (limit) $\sim d^{-1}$ relation is obeyed quite well.

For rectangular tubes two spin mod's are covers a near the
limits of detonability. The one fits to the long .-de,
the other one, with higher frequency to the short side of
the rectangular cross section. The above mentioned argu-
ment could lead to the conclusion, that the lowest (or the
higher) of both frequencies determines the limit of deton-
ability. If that is so the length of one of the two sides
of a rectangular tube should be nearly the same as the
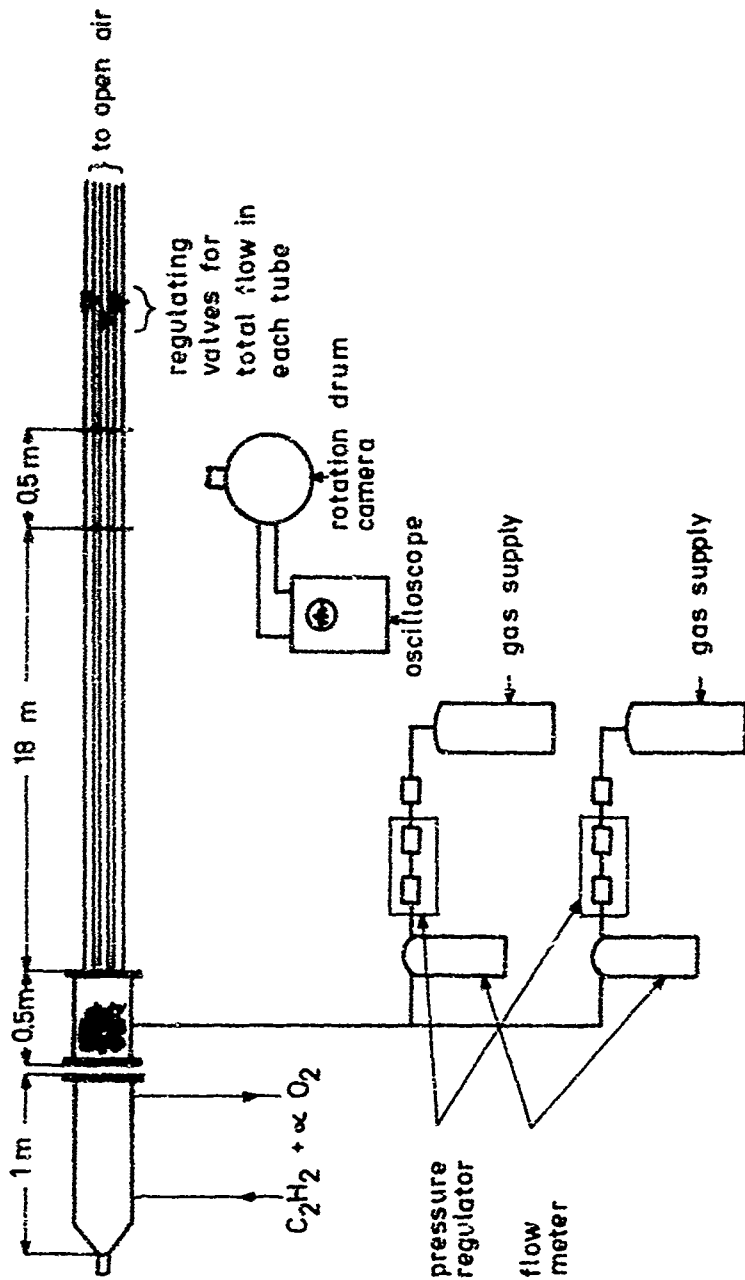diameter of a circular tube at the limit of detonability.

Fig. 1   Experimental set up for Measurements of the Influence of Tube Shape on the Limits of Detonability

Experimental Arrangement

The influence of the shape of the detonation tube on the
limits of detonability has been investigated in an
apparatus described below:

Three tubes are mounted parallel. The flow resistance of
the tubes are made equal by proper choice of an end piece
of each tube which is two meters apart from the windows.
The whole length of the tubes is 20 meters. Windows are
made from plexiglass, 40 cm long, and mounted flush into
the tubes. For the experiments the windows of the various
tubes are arranged one above the other with 1 cm distance
inbetween. Each tube is signed by two Tesa strips with
characteristic distance so that the picture of each tube
can easily be recognized on the film.

The ignition section consists of a 1.5 meter long tube
of 9 cm diameter and a spark gap at the closed end. The
tube is filled over a distance of 80 cm with a wire
entanglement in order to improve the establishment of the
initiating detonation. (Mostly an adjusted $C_2H_2-O_2$ mixture)
It is connected with another tube of the same diameter
(with a thin diaphragm between both). In the end plate
of this section the detonation tubes are mounted.

This section and the detonation tubes are filled
simultaneously with the same mixture (clean CH_4-O_2).
Mixture compositions are measured by capillary flow
meters connected to the gas supply by two successive
constant pressure valves. An additional valve is mounted
at the steel tank. Calibration of the flow meters is
done with precision gas meters.

Variation of the gas composition should have a negligible
influence on the results because the experiments are
performed, such that detonations in one or two tubes fail,
while the third tube still shows stable detonation. Taking
a mixture in some distance from the limit, the three
detonations arrive at the same time at the windows.
Coming closer to the limits of detonability, detonations
start to fail and the arrival of the combustion processes
at the windows does not take place at the same time
anymore. The absolute values of the detoration limits
are therefore not as precise as the relative data.

In the past, measurements of limits of detonablility have
been performed with an apparatus in which the detonation
tubes reached about 15 cm into the initiation section.
This has been done in order to delay the influence of
the reflected detonation. With the rectangular tubes used,

it was found, however, that under these conditions the
tube is deformed in the inition section so that un-
reliable results have been obtained. Therefore the
connection of the detonation tubes with the initiating
section have been changed and the tubes were mounted
flush into the end plate. For tubes with circular cross
section this did not influence the limits of detonability
much; the same may be assumed for tubes of other shape.

The rectangular and the square cross section brass tubes
(1 mm wall) in addition are supported by steel bars on
the long side over the whole tube length. This is necessary
because otherwise at places where apparently detonations
start, the tubes are deformed or destroyed. At the
place where the windows are mounted all tubes are supported
against deformation by steel constructions. The pressure
in the tubes filled with gas mixture has been atmospheric
pressure in all cases. No correction for variations of the
atmospheric pressure has been applied. Temperature of the
mixture was 20 °C $\pm$ 1 in all experiments. After each
experiment the tubes were cleaned and dried by blowing
dry nitrogen through for a while. Every day the leak rate
and the cross section of tubes were checked.

Experimental Results

For the experiments the following tubes have been
used:

Circular cross section

Diameter (cm)		2.0 (A)	1.8 (B)	0.8 (C)
Area	(cm^2)	3.15	2.54	0.5
Hydraulic radius	(cm)	1.0	0.9	0.4
Hydraulic diameter	(cm)	2.0	1.8	0.8

Square cross section

Side length	(cm)	1.8 (D)	1.6 (E)
Area	(cm^2)	3.24	2.55
Hydraulic radius	(cm)	1.02	0.902
Hydraulic diameter	(cm)	2.04	1.804

Rectangular cross section

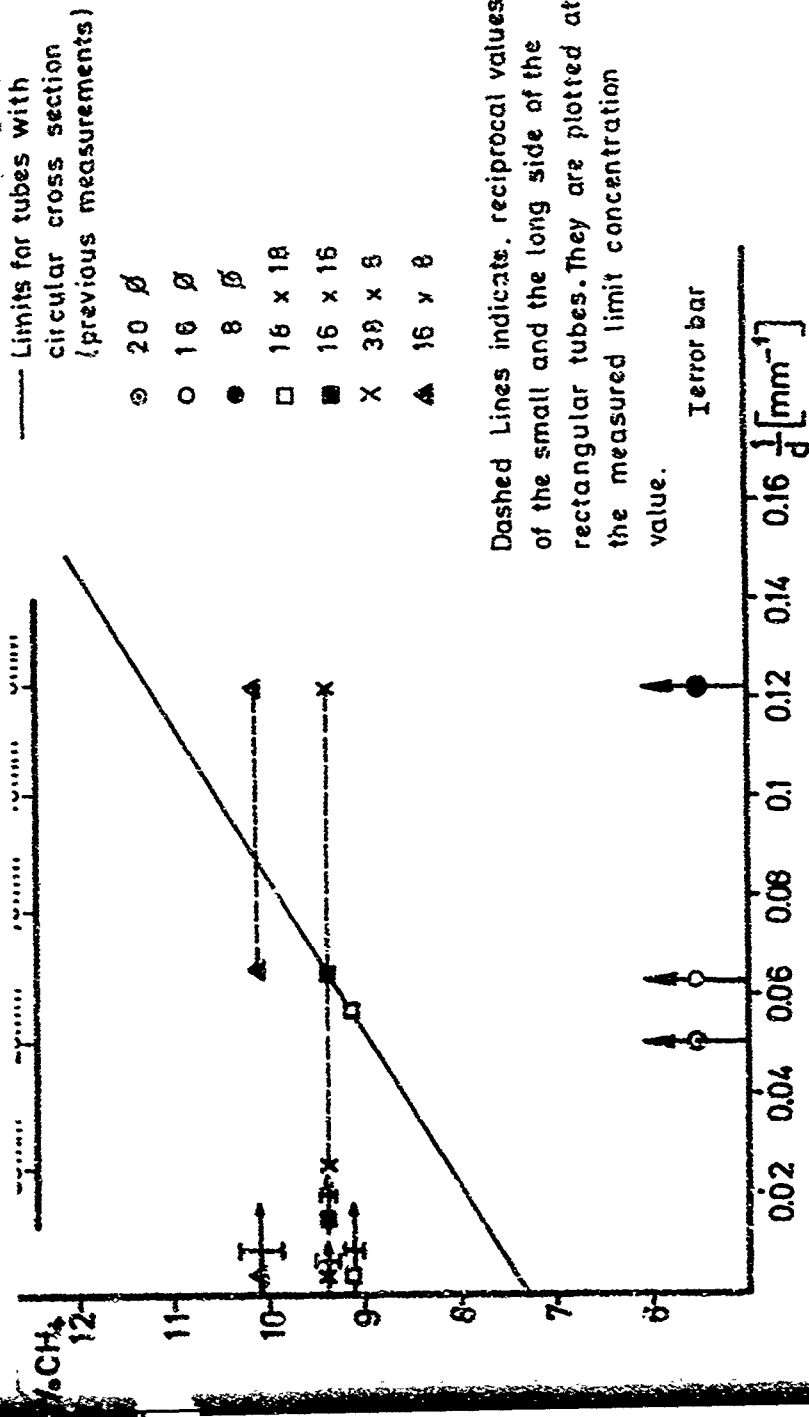| Long side	(cm)	3.8 (P)	1.6 (G)
Short side	(cm)	0.8	0.8
Area	(cm^2)	3.04	1.28
Hydraulic radius	(cm)	0.985	0.64
Hydraulic diameter	(cm)	1.97	1.28

Fig. 2 Limits of Detonability for lean $CH_4 - O_2$ Mixtures for various Tube Shapes and Diameters

For tubes with circular cross section previous results
could be confirmed within the limits of experimental
error. The limit concentration is a linear function of
the reciprocal tube diameter.

The two tubes with square cross section behave in a
similar manner. For the tube with larger side length
the limits of detonability are slightly wider than for
the other one. The absolut values of the concentrations
at the limit seems to fall on the line for tubes with
circular cross section in the C(limit), 1/d plott if
the side length is taken as d. The hydraul·. diameters
of the square cross section on tubes are a little larger
than the side length. They do not fit as well in the
C(limit) - d^{-1} plott as the side length. In case of
tube D the limits are definitely narrower than for tube A
while the hydraulic diameter is larger. The differences
are, however, small.

A different situation arises for the rectangular tubes.
Here neither the long side nor the short side nor the
hydraulic radius fit into the line C(limit) - d^{-1}.
The limits of detonability for the 3.8 x 0.8 rectangular
tube are definitely narrower than those for the tubes A,
D and B. They roughly correspond to those for 1.6 cm

square tubes while the limits for the 1.6 x 0.8 rect-
angular tube are still narrower.

If the smallest distance in the tube would determine the
limits both rectangular tubes should nearly coincide
with the 0.8 cm diameter circular tube. Apparently the
1.6 cm long side widens the limits about 1 % while the
3.8 cm side widens them about 1.6 % compared to the
limit for infinite tube diameter, which in the present
case is about 4 % away.

The hydraulic diameters for these tubes do not fall on
the $C(limit) - d^{-1}$ line either. However, the line
connecting the hydraulic radii at the limits for the
rectangular tubes seems to be parallel to the $C(limit)-$
d^{-1} line for the circular cross section tubes. Roughly
one can say that an estimate of the limits of detonability
based on the hydraulic diameters gives a reasonable value
which in the case under discussion here fits better than
1 %. It is obvious, however, that this is not a good
description of the real process. Apparently a correct
stability analysis has to take into consideration the
details of the interaction process between chemical reac-
tion and flow inside and behind the reaction front. To
a certain degree, however, the correlation with the
hydraulic diameter seems to be a reasonable approximation

as long as one side is not to narrow. It is to be expected,
that there exists a condition, that the small side of the
rectangle hasto be larger than a lower limit d_1 , which,
however, is definitely smaller than the limiting diameter
for tubes with circular cross section. For very large
tubes (in each dimension) the shape of the tube should
have nearly no influence on the limit of detonability for
infinite tube diameter. That would require, that, if one
wants to keep the linear relation at the limits of deton-
ability for C(limit), d^{-1} there exist limit lines which
depend on the shape of the cross section of the tube.
This influence is, however, not very pronounced, even
a ratio of the sides of a rectangular tube close to 5:1
gives only a deviation, based on the hydraulic radius
of less than one percent. On that basis it can be under-
stood, why attempts for a quantitative description of the
limits of detonability and the influence of tube diameter,
pressure, temperature and other parameters on these limits
have not been very successfull in that rough models could
be improved and put on a quantitative basis.

Some Experiments on the Propagation of Spherical Flames

Introduction

The soap bubble method is a well known method for deter-
mination of flame speeds A. If the expansion radio $\mathcal{S}_1/\mathcal{S}_0$
is known one obtains the flame speed by measuring the
rate of propagation of the flame area

$$A = \sigma \cdot \mathcal{S}_1/\mathcal{S}_0$$

In most of the experiments reported in the literature the
spread of the flame on the film, (taken by a smear camera)
is a straight line indicating constant values of   . The
flow situation for such a case is shown in Fig. 3. The gas
ahead of the flame is shifted away from the center. The
pressure increases from a very weak front shock towards
the flame front. Behind the flame the gas is practically
at rest. Flame velocities obtained by the soap bubble
method are in good agreement with values obtained by other
methods.

There are, however, indications, that the flame propagation
does not take place as smoothly as one might expect from
the fact that the measured flame velocities are all right.

Troshin published schlieren pictures of flames which indi-
cate cellular structure of the flame front. Measurements
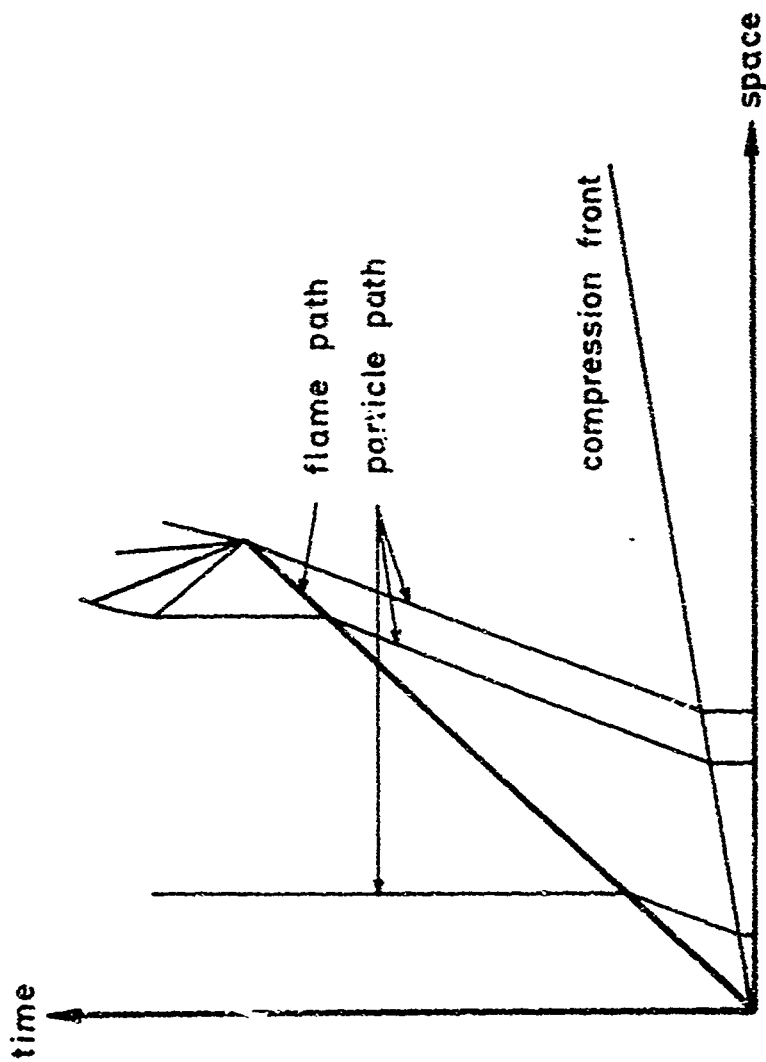of flames in constant pressure bombs often give not only

Fig .3   World Line of Stationary Spherical
Flame

wrong absolute values of Λ but also a wrong pressure depen-
dence of the flame speed. Investigations of sound generated
by flames also indicates a structure.

Kogarho reports that flames in propane oxygen mixtures,
ignited by a spark can accellerate and show transition
into detonation.

Istratov performed calculations on the stability of spheri-
cal flames. These calculations gave a critical Reynoldsnumber
based on the radius for the stability of spherical flames.
The value of this critical Reynoldsnumber, however, is far
away from the one obtained by Troshins experiments.

The problem of stability of spherical flames is of funda-
mental importance for explosions of free gas clouds. The
central question is: which mechanism leads to flame
accelleration?

In tubes it is obvious: the unburned gas, flowing ahead of
the flame can become turbulent and this can lead to pro-
gressive flame accelleration, generation of shock waves
and so on, a well known process. The immediate generation
of interacting shock waves normally takes place only in a
later stage of the process.

There are indications that the disturbance of the flame
front in bomb explosions and also in some soap bubble
experiments are generated by reflected pressure waves.
Especially in bomb explosions this could clearly be
shown. The first step in air experiments therefore had
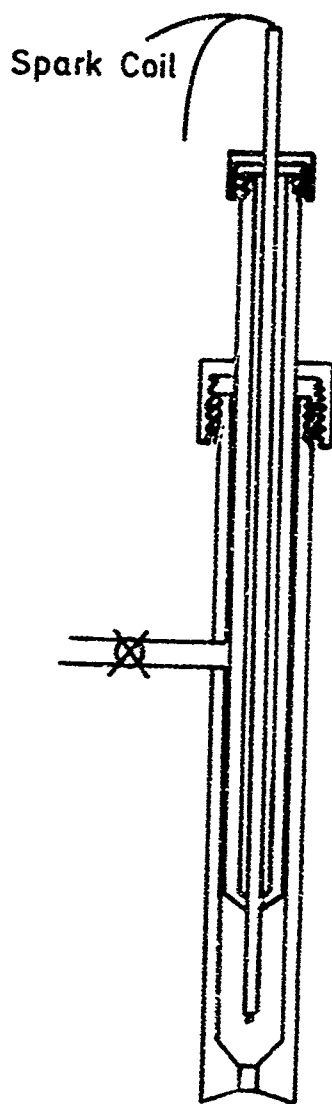to be to find an experimental arrangement to minimize
that influence.

Fig. 4   Soup Bubble Generator

Experimental Arrangement

The gas mixture is prepared by capillary flow meters
with pressure stabilized supply. Part of the con-
tinuous flow is extracted through a soap bubble generator
via a special valve. If the bubble reaches the wanted
diameter this valve is closed. The soap bubble generator
(Fig. 4 consisted of a plexiglass tube (1.5 cm diameter)
with a piston inside. This piston contained the electrodes.
It was constructed such that it closed the flow inlet as
well as the gas exit to the soap bubble. This bubble
generator was mounted on a 1 cm stell bar. There were
no solid walls around the bubble at distances below 1 m
so that reflected waves needed at least 1/150 sec to come
back to the scap bubble. For flame speeds in the order of
one meter per sec and about 10 cm bubble diameter this
means that reflected sound waves do hardly come back as
long as the bubble burns. The bubble generator itself was
mounted by thin long metall tubes. Sound waves reflected
at these tubes can come back to the flame. They are, how-
ever, highly attenuated. This had to be accepted because
the ideal method, free gas bubbles ignited centrally by
laser radiation would have been much to complicated in
that phase if the investigation.

The smear camera is mounted about one meter away from
the soap bubble. The soap bubble is projected into
an image plane where a slit takes away most of the
picture; only a small horicontal strip of the bubble
is then projected on the film for measuring the flame
spread.

Experimental Results

In order to check the reliability of the system flame
velocities of CH_4-air and H_2-air mixtures have been
measured and found to be in good agreement with litera-
ture data. Then the following systems have been in-
vestigated

CH_4 — α air

CH_4 — α-air (with 50 % O_2)

CH_4 — α air (with 80 % O_2)

CH_4 — α-O_2

H_2 — α-air (with 50 % O_2)

H_2 — α-O_2

$(CH_4 + H_2) + \alpha O_2$

C_2H_4 — air

C_2H_4 — O_2

C_2H_2 — air

C_2H_2 — (air with 50 % oxygen)

C_2H_2 — O_2

In all these systems which were investigated in soap
bubbles of 7 cm diameter not the slightest indication
of a flame acceleration could be observed. (Ignition
by an engine spark)

The experiments continued with attempts to generate
larger soap bubbles. For the methane, the (CH_4+H_2) and
the C_2H_4 systems bubbles of 15 cm diameter could be
generated. For C_2H_2 – air and for C_2H_2 – O_2 bubbles up
to 12 cm could be formed.

The photographs of these flames (each mixture has been
used 3 to 5 times at different days) also did not indi-
cate any acceleration of the flames.

These results indicate that up to about 15 cm diameter
of the gas ball there seems to be no internal mechanism
which accelerates flames (even in mixtures with O_2) so
that transition to detonation takes place. At least in
that range of diameters of the bubble external mechanisms
must have been active in the experiments of other authors.

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